A low-cost High Spectral Resolution Lidar for measurement of aerosols and clouds optical properties

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Abstract: We present an improved prototype of a low-cost High Spectral Resolution Lidar developed by our group at the University of Wisconsin. The lidar transmitter is based on commercially available diode laser components: a distributed feedback diode (DFB) laser and two semiconductor optical amplifiers; it operates at 780 nm and uses Rb D2 absorption line for signal discrimination. In this paper we describe an improved instrument design, and present the aerosol backscatter and depolarization ratio measurements of aerosols and clouds performed by the prototype system.

1. Introduction

HSRL systems have been under development at the University of Wisconsin since the 1970's [1]. The High Spectral Resolution Lidars (HSRLs) developed at University of Wisconsin - Madison have proven to be reliable and provide robust measurements of aerosols and clouds optical properties at both 532 nm and 1064nm wavelengths [2]. The UW instruments have been deployed in various parts of the world, and recently provided measurements for the CAMP^{2}Ex, PISTON, and MAGPIE field campaigns. With the upcoming AOS and other future space-based lidar missions, there is a potential need for a network of HSRLs that can supersede the micro pulse lidars (MPLs). While the UW-HSRLs provide robust high-fidelity measurements, a network of HSRLs at 532 nm and 1064 nm wavelength are expensive since each HSRL is costly to develop and require specialized skills to maintain.

With the vision of reducing the total cost of the HSRL, recent advances have been made in adopting commercially available telecommunication optical hardware and use the adopted hardware to develop a lower cost HSRL [3]. The UW lidar research group has developed a prototype low-cost HSRL with a transmitter based on commercially available diode laser components: a distributed Bragg reflector (DBR) diode laser and semiconductor optical amplifier [4].

In this work we describe the instrument design, and present the aerosol backscatter and depolarization ratio measurements of aerosols and clouds performed by the prototype system.

2. Instrument design

The prototype of a new low-cost HSRL has a concept similar to previously built lidars, operating through a single telescope to transmit and receive light. This reduces the energy density in the transmitted beam and improves mechanical stability allowing it to operate with a small field-of-view. The CAD model of the instrument is shown in Figure 1.

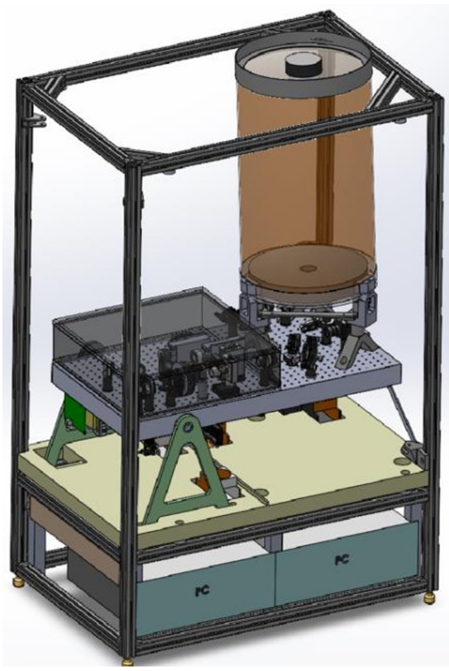

Figure 1. The HSRL CAD model. Thermal panels are removed.

The instrument operates at 780 nm wavelength and has two semiconductor optical amplifiers which can together transmit up to 50 mW of average power at 8 kHz pulse repetition rate. The lidar parameters are shown in Table 1.

Table 1. Lidar Parameters

Transmitter	Value/Type
Laser	Semiconductor Optical Amplifier
Wavelength	780 nm
Maximum Transmitted eye-safe power	50 mW
Spectral purity	~1:500
Frequency locking accuracy	±8 MHz
Pulse repetition rate	8 kHz
Pulse duration	0.25 -1 μs
Telescope aperture	14" shared
Receiver	**Value/Type**
Telescope type	Schmidt-Cassegrain
Field-of-view	100 μrad
Bandwidth/Fe/T peak	~8.5 GHz/22/88%
Rb85 D2 line width	~1 GHz
Number of detectors	2
Number of Channels	8

The DBR diode master oscillator is continuously modulated at 4 kHz. The semiconductor optical amplifiers are fired at the frequency extremes to form alternate laser pulses which are on- and off- the rubidium absorption line. This approach enables a single-detector receiver architecture for HSRL measurements and avoids alignment errors associated with different optical paths and detector sensitivity.

The transmitter diagram is shown in Figure 2.

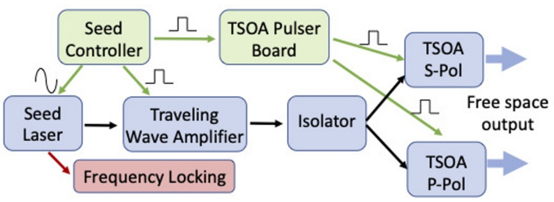

Figure 2. Transmitter diagram

The optical components are mounted on two sides of the optical breadboard. Transmitter and receiver sides of the breadboard are shown in Figures 3 and 4. The outputs of the two optical amplifiers has orthogonal polarizations and are merged at the polarizing beamsplitting cube. A leakage through the cube is used to monitor the transmitted output power, see Figure 3.

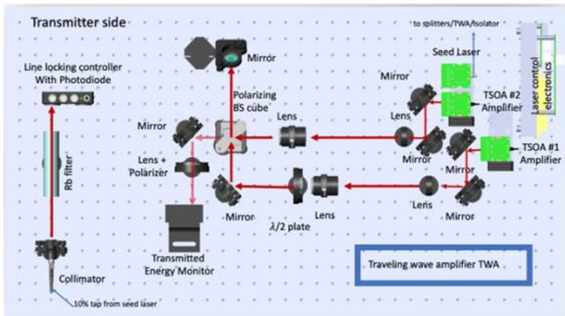

Figure 3. Transmitter side of optical bench (bottom side)

A custom-made mirror with a 5 mm bored hole is used as a transmit/receive switch, see Figure 4. The optical axes of the transmitter and the receiver are separated by ~15 mm at this mirror and ~305 mm at the telescope aperture. A telescope coupling lens with 200 mm focal length provides 20x telescope magnification. The transmitted beam diameter is around 100 mm. The mirrors of the 14" amateur Celestron telescope are recoated with protected gold coating.

The received signal is passing through an interference filter with a bandwidth of 0.4 nm. The air spaced Fabry-Perot etalon with 8.5 GHz bandwidth further suppresses the sky noise for daytime operation. The etalon has fused silica spacers which enable thermal tuning. It is pre-tuned by pressure and then thermally tuned by automated algorithm every 24 hours after routine calibration frequency scans.

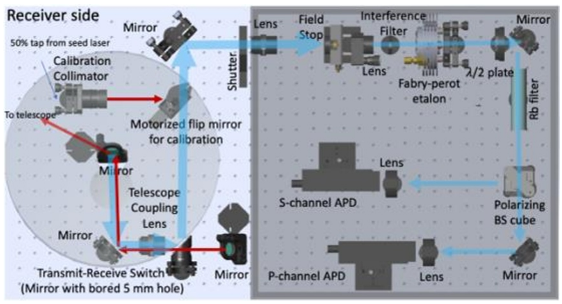

Figure 4. Receiver side of the optical bench (top side)

Then, the received light passes though the spectroscopic Rb85 filter. The cold finger of the cell is controlled at 30 C with stability of ~20 mK, and the windows are controlled at 38 C to prevent deposition of Rb on the windows.

The light is then split between S- and P-polarized channels. Single photon avalanche diode detectors by Excelitas are used in the instrument and provide ~70% quantum efficiency at 780 nm.

3. Operating modes

The instrument is designed with a flexibility for controlling pulse duration and frequency on a shot-by-shot basis, and the sequence for S-polarized and P-polarized laser transmitters. The custom developed data acquisition system is synchronized to the different transmitter modes and stores signals in the corresponding data buffers.

The current configuration includes a sequence of the three modes: in the first mode both amplifiers are transmitting 1 µs long pulses for both on-line and off-line pulses. In the second mode S-polarized amplifier transmits 1 µs long on-line pulses and 500 ns long off-line pulses. In the third mode the P-polarized amplifier uses 250 ns for both on-line and off-line pulses. For all of the modes the frequency is continuously modulated on shot-by-shot basis, and every 20th shot is skipped for background noise measurement. By varying the pulse length and amplifier sequence the instrument achieves a higher vertical resolution, higher dynamic range (which makes the low gain detector redundant) and depolarization measurement.

4. Data examples

An example the HSRL data are shown in Figures 5 and 6: range-time image of aerosol volume backscattering coefficient and coefficient for linear depolarization.

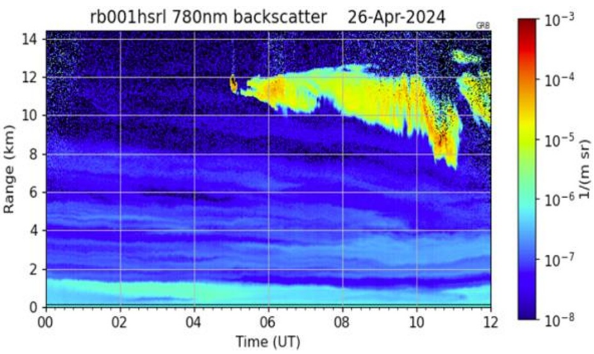

Figure 5. Aerosol volume backscattering coefficient, April 26th, 2024 0:00 – 12:00 UTC, Madison, WI

On April 26th, 2024 the instrument detected ice clouds between 10 and 12 km altitude from 5:00 to 12:00 UTC; a persistent aerosol in the boundary layer and a thinner residual aerosol layers from 0:00 to 12:00 UTC.

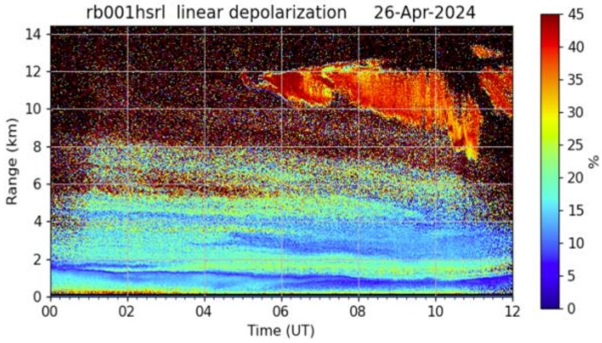

Figure 6. Linear depolarization coefficient, April 26th, 2024 0:00 – 12:00 UT, Madison, WI

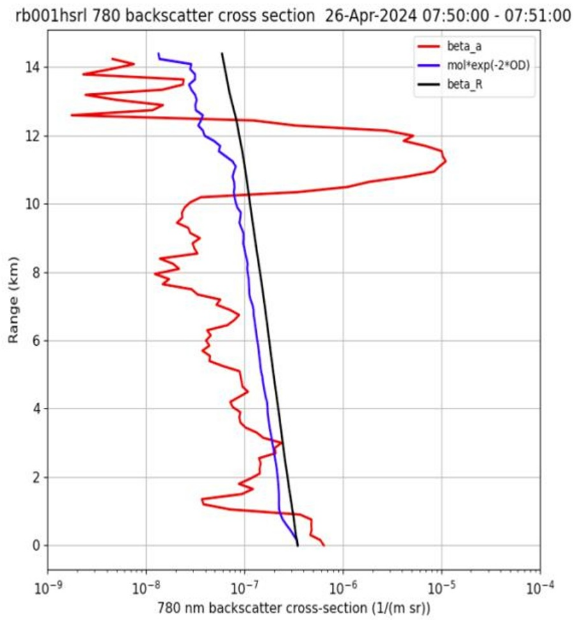

Figure 7. Aerosol volume backscattering coefficient (red), attenuated molecular backscatter (blue), calculated molecular backscatter (black) April 26th, 2024 7:50 – 7:51 UTC, Madison, WI

5. Conclusion

We described our prototype of the cost-efficient High Spectral Resolution Lidar and demonstrated the data measured by the instrument. Further development of the ruggedized version of the instrument will be pursued. The work toward the robust measurement of the extinction cross-section and lidar ratio will be continued.

6. Acknowledgement

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7. References

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